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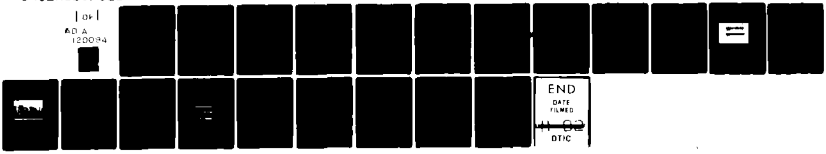

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Plasma Waves Stimulated by Electron Beams in the Lab and in the Auroral Ionosphere

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1 October 1982

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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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Energetic electron beams are frequently used as active probes of space plasmas. Often the assumed test particle nature of these electrons is violated when the electron beam stimulates plasma wave emissions. Such complex phenomena have been observed on rockets and satellites and are being modeled in laboratory plasmas. The large vacuum chamber at NASA Johnson Space Center in Houston, Texas has been used for modeling F-region type ionospheric plasmas. A VLF receiver has been flown into an auroral plasma and the spectra from this flight

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will be compared to VLF spectra obtained in the NASA/JSC laboratory chamber. The electron beam is believed to have produced beam plasma discharge (BPD) on the rocket similar to that seen in the lab. At times during the rocket flight the electron beam was operated at 4 kilovolts and the electron current modulated at 3 kilohertz from 0 to 80 milliamps. This resulted in the beam pulsing in and out of BPD and a variety of propagating wave modes.

The laboratory VLF electric field spectra during BPD show a characteristic peak at a few kilohertz with amplitudes over 100 mV/m. This peak broadens and moves to higher frequencies as the current is increased at a fixed electron voltage. Other features of BPD in the lab as seen in the VLF spectra include appearance of the spectral peak prior to optical BPD threshold, differences between $\tilde{E}$ and $\tilde{B}$ spectra below the peak, and oscillation in and out of BPD, even under a steady-state electron gun current on time scales of 100 ms.

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INTRODUCTION

In an active experiment to study plasma dynamics in the auroral ionosphere, NASA sounding rocket 27.010 AE was launched on April 9, 1978 from Ft. Churchill, Manitoba, Canada. The rocket carried an electron accelerator and a full complement of plasma diagnostic devices including electric and magnetic receivers, particle detectors and photometers. The accelerator was mounted on the aft payload which remained attached to the rocket motor throughout the flight. The diagnostic devices were arranged on various Throw Away Detectors laterally ejected (TAD's) and a forwardly ejected payload. One important experiment performed in this flight (described in detail by Holzworth and Koons, 1981) involved the 3 kHz modulation of the electron beam current at fixed voltage and the subsequent detection of a 3 kHz signal by electric and magnetic receivers on the forward payload at distances up to several kilometers away. Furthermore, steady state gun operation at maximum current appeared to result in beam plasma discharge (BPD).

Following ejection of the forward payload at about 10 m/s and antenna deployment, the electron accelerator on the aft payload was operated in a mode in which the current was modulated between I_{min} = 0 to 10 mA and I_{max} = 80 mA at 3 kHz for 450 ms every 11 s. Every one of these accelerator modulation periods (AMP's) was detected by the forward payload in the electric VLF spectrum. In the first half of this paper the wave spectra from the rocket flight will be discussed. In particular the spectral features indicative of beam plasma discharge will be emphasized. This includes a time delay analysis which suggests that a variety of wave modes were present and the presence of a characteristic spectral enhancement near a few kHz during pulsed gun operation. A more detailed description of the 3 kHz VLF spectra from flight 27.010 may be found in Holzworth and Koons (1981).

The second half of this paper deals with experimental laboratory simulation of the ionospheric rocket observed phenomena. The experiments were conducted in the large vacuum chamber (see Bernstein et al., 1981) at the NASA Johnson Space Center in Houston, Texas. In this chamber we have conducted experiments to simulate the ionospheric phenomena seen by several rockets launched into the auroral ionosphere. Of particular interest is the beam plasma discharge (BPD) phenomena wherein the electron gun, when operated above some threshold current for a given energy, produces a vastly enhanced ionization rate in this collisionless environment. Lab studies of BPD at the NASA/JSC chamber have been conducted for some time (Bernstein et al., 1978). These investigations have shown that the radio frequency waves above 1 MHz may not be large enough in amplitude to provide the necessary energization for BPD (Bernstein and Kellogg, 1980). In these studies relatively low-resolution measurements in the VLF spectrum suggested that these very low frequency waves were responsible for the energization. Therefore the last half of this paper will characterize these low-frequency electric and magnetic waves during BPD with high-resolution spectrograms.

Variations in gun energy and current result in differing thresholds for the BPD, which are reflected in these spectra. VLF spectrograms obtained during the NASA rocket flight 27.010 AE (E||B) from Ft. Churchill in 1978 will be compared to these lab plasma spectrograms. This comparison strongly suggests that BPD phenomena were responsible for the measured spectral features from the rocket.

Rocket Instrumentation

The payload instrumentation have been described by Wilhelm et al., 1980 and by Bernstein et al., 1981. The rocket instruments relevant to this work are the electron accelerator and the wave receivers. The VLF wave receiver has been described in Holzworth and Koons (1981). Briefly, the VLF instrument includes an electric antenna consisting of a pair of spherical probes separated by 2.75 meters on rigid booms mounted ⊥ to the spin axis and a magnetic antenna consisting of a ferrite rod with multiple windings mounted inside the forward payload. The preamps fed both broadband (up to 16 kHz) and fixed-frequency, narrowband channels. One of these narrowband filter channels was set at 3 kHz, which allowed accurate determination of absolute signal amplitudes for the 3-kHz AMP's. All electronics in these receivers operated perfectly except that onboard EMI away from our range of interest caused the magnetic AGC to operate in its least sensitive mode throughout the flight. Thus the broadband magnetic spectra are considerably more noisy than the electric.

Rocket Observations

In Holzworth and Koons (1981) it was shown that a VLF signal at 3 kHz was clearly radiated during the beam modulation periods. An important point made in that paper was that the time delay between the beginning of electron accelerator modulation periods (AMP's) and the onset of the detection at the forward payload was not only measurable but variable over the flight. Fig. 1 shows these measured time delays vary from near zero to several tenths of a second. Furthermore, the point was made in that paper that the electric and magnetic signals from the AMP's were not received simultaneously but sometimes the electric signal preceded the magnetic and sometimes the other way around.

The propagation time for the 3-kHz signal to reach the forward payload is often significantly slower than for an electromagnetic wave which could not be resolved on this time scale. The apparently systematic changes in the time delays shown in this figure suggest that the signals are not simply space charge disturbances emanating from the aft payload. Since the modulation was between 0 and 80 mA at 4 kV, the beam was probably pulsing in and out of BPD.

A 20-second sequence of spectral data from the electric receiver on the rocket is shown in Fig. 2. This spectrogram shows several

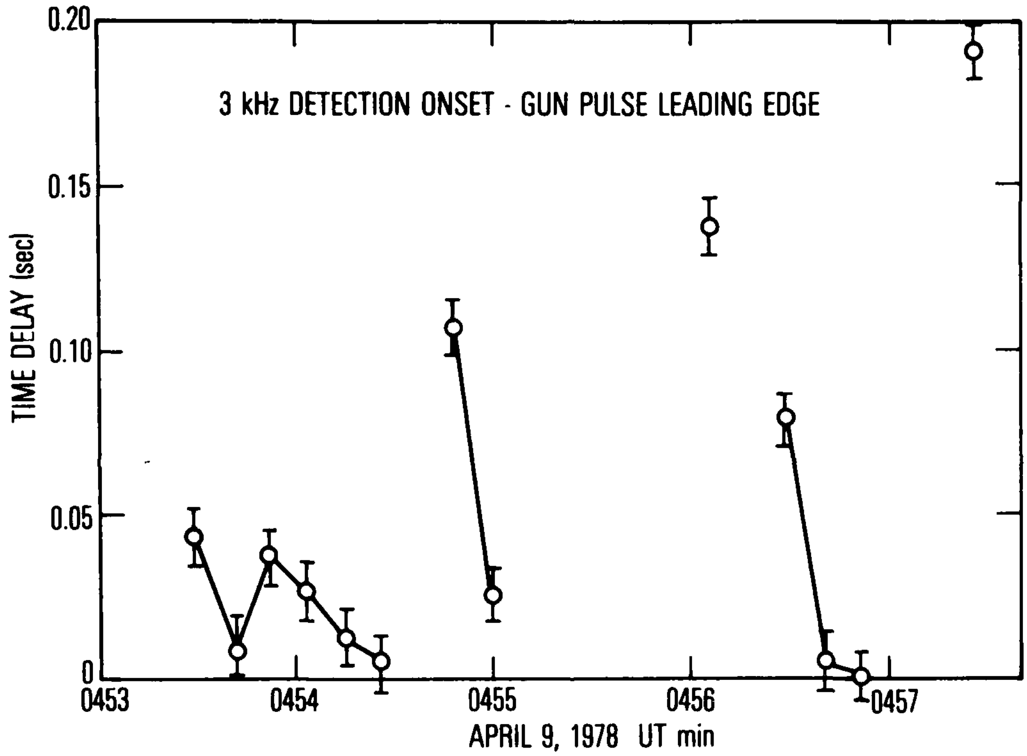

Fig. 1. Time Delay between Turn-On of Gun AMP and Detection at Forward Payload. Data gaps are due to irregularity of occurrence of AMPs and interference by other VLF phenomena.

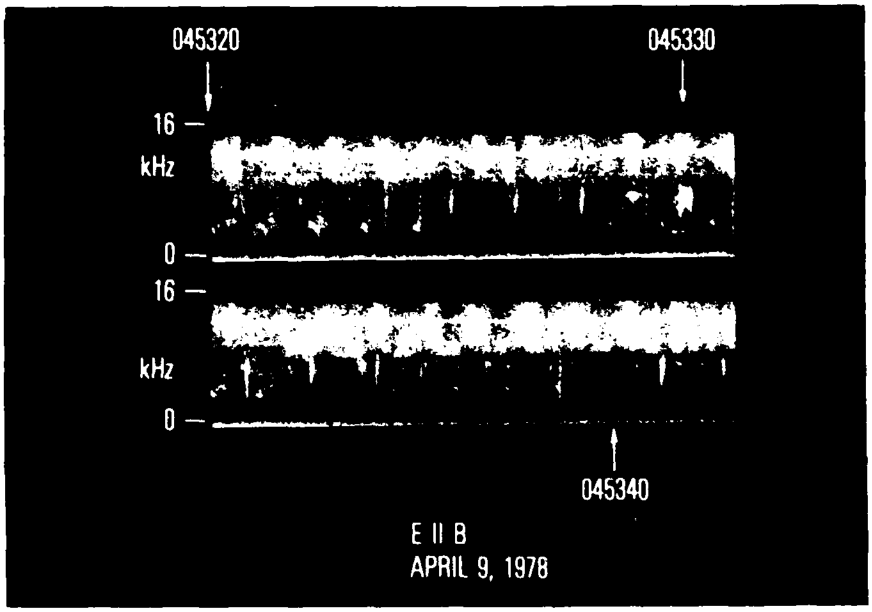

Fig. 2. A 20-sec Electric Spectrogram from E||B. The distinct broadband pulses are due to the dc gun steps at 2 and 4 kV at the maximum current.

discrete broadband pulses which occurred during gun operations at 2 and 4 kV. These dc pulses were of 50 ms duration and the sequence repeats about every second. A longer pulse of 450 ms occurs near 04:53:30 UT. During these larger pulses (AMP's) the current was modulated at 3 kHz as discussed above. The spectra during AMP are very similar to the dc steps but show considerable time variability. Enlarged spectra during some of these pulses are shown in Fig. 3. Broad spectral peaks near 5 or 6 kHz are seen to extend up to the lower hybrid frequency which is a little above 7 kHz.

Laboratory Experimental Apparatus

The chamber set-up used in these experiments included an electron gun on a movable cart on the floor of the chamber, with a target collector for the electron beam mounted near the top of the chamber. The ac electric and magnetic antennas were mounted near the center of the chamber, just outside the gun generated plasma column. Various other particle and field measuring devices were also available which are discussed elsewhere (Bernstein et al., 1978). The electron gun voltage and current were individually varied from 0 to 2 kV and 0 to 80 mA respectively.

The electric receiver consisted of a pair of crossed 2-foot dipole antennas connected to high-impedance preamplifiers followed by various attenuators and amplifiers in the chamber, providing a dynamic range of 160 db above 100 nanovolts. The electric antennas were mounted on a two-pulley arrangement allowing location anywhere in a plane which intersected the gun plasma column. The magnetic antenna consisted of a two-foot-diameter loop with 2000 turns of wire having pick off points at 20, 200 and 2000 turns. Magnetic sensitivity extended down to 0.2 picotessla at 3000 Hz. The dynamic range was 110 db. The loop was mounted on a fixed support rope about 3 meters from the gun plasma column. The vacuum chamber was cryogenically pumped at liquid helium temperatures and maintained a pressure of about a few times 10^{-6} torr throughout these experiments.

Laboratory VLF Spectral Data

Fig. 4 shows a sequence of electric and magnetic spectra during electron gun operations at 2 kilovolts and varying current from 9 mA to 48 mA. In this mode the gun was operated in a dc manner while the background plasma thruster was off. These spectra are averaged data for about one second and show the general sequence of signature variation from single particle behavior in panel a at 9 mA to a supersolid BPD in panel e. The determination of BPD onset was provided by optical instrumentation including narrowband photometers and a low-level-light TV system.

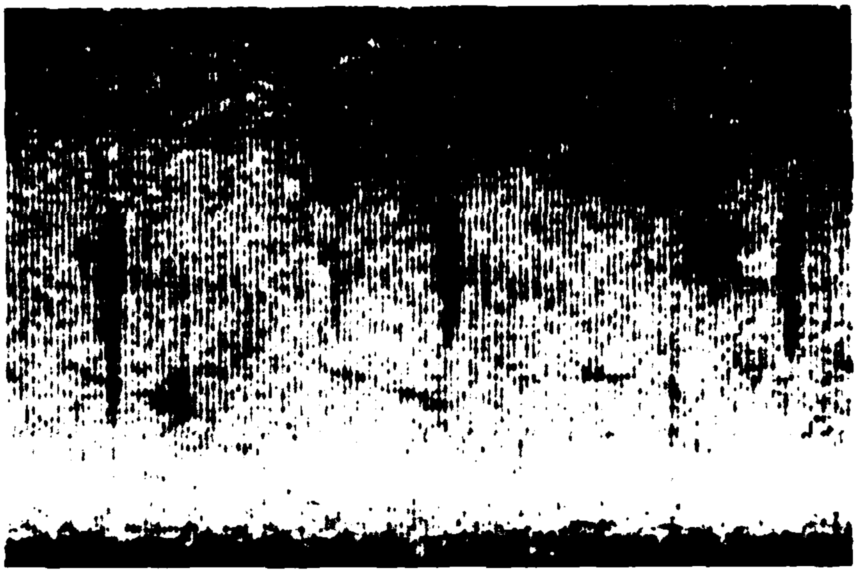

Fig. 3. Rocket Observed Electric Spectra during Pulsed Mode Operation. This is an expanded section of Fig. 1 starting at 04:53:31 UT.

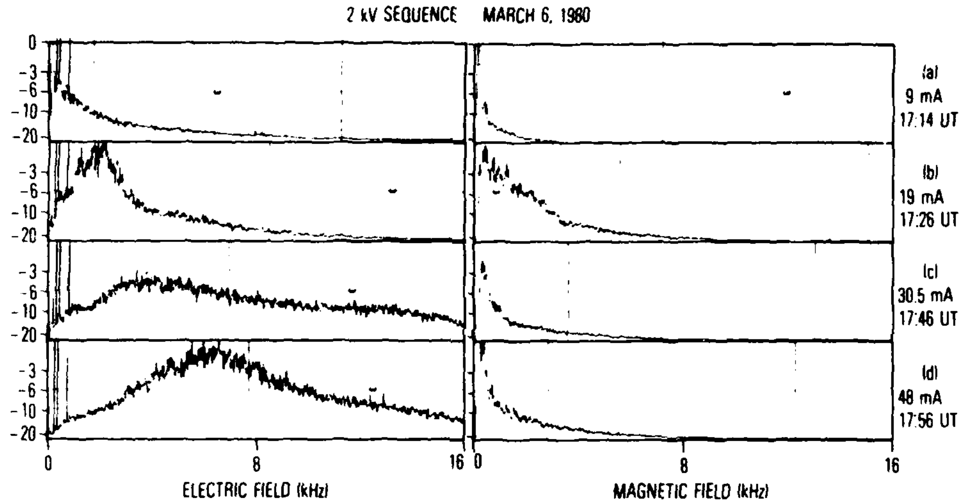

Fig. 4. Electric and Magnetic Spectra during Electron Gun Operation at 2.0 kV. a. Single particle spectrum at 9 mA; Odb = 13.4 mV or 1.2 mγ. b. Prior to BPD threshold at 19 mA; 0 db = 84.5 mV or 0.38 mγ. c. Solid BPD at 30.5 mA; 0 db = 42.4 mV or 1.1 mγ. d. Supersolid BPD at 48 mA; 0 db = 42.4 mV or 1.5 mγ.

Fig. 4 panel b is a spectrum from just prior to BPD conditions as determined optically. However, a well-developed broad peak has already appeared in the VLF electric signal near 2.2 kHz. The sharp narrowband peaks in the low-frequency electric signal are 60-cycle harmonics. A sharp onset of BPD occurs within a milliamp change in the electric current. As the current is increased to 30.5 mA, a solid BPD is formed (see Fig. 4 panel c) and the VLF peak of panel b has become substantially broader and the tail more enhanced. Now the magnetic spectrum is radically different and appears more like a single-particle spectrum. Finally, the current is raised to 48 mA in Fig. 4 panel d and the peak and tail are both broader and more enhanced in the electric signature.

The 2-kV BPD ignition sequence is summarized by three electric VLF spectrograms in Fig. 5. Here it is seen that the spectra also became time-variable on the scale of a few hundred milliseconds, appearing to turn BPD on and off. This effect is averaged out in the one-second average spectra of Fig. 4.

As an example of another gun energy, Fig. 6 presents an ignition sequence at 800 volts. Here the BPD threshold occurred at 7.8 mA and the VLF peak progressively moved to higher frequency as the gun current was raised to the "supersolid" 30-mA, 800-V level. At this energy, unlike 2 kV, the magnetic signature (not shown) is very similar to the electric except for the very low frequencies.

To investigate the time variability we operated the gun in a pulsed mode with 80 msec on and 250 ms off at 2 kV and 70 mA. Fig. 7 shows a sequence of raw spectral traces during one of these pulses with no background plasma. As the gun comes on, the spectrum looks like a single particle spectrum (bottom of Fig. 7, compare this to Fig. 4a). Then within a few milliseconds the spectrum begins to look like a BPD spectrum (compare to Fig. 4d) with a broad peak near 6 to 10 kHz. Apparently this is an indication that some background plasma must be built up by the beam before the BPD onsets. DC-field strengths over 10 volts/meter were measured near the BPD threshold condition in very burstlike events.

Rocket/Laboratory Spectral Comparison

Figs. 2 and 3 from the rocket flight can be compared directly to Figs. 4 through 7. The rocket clearly shows broadband spectral enhancements from a few kHz up to a cutoff at the lower hybrid frequency. In this frequency range a clear peak occurs at about 5 to 6 kHz in Figs. 2 and 3. This is exactly the region of frequency space where the lab spectral peaks were seen. Furthermore the lab VLF spectral peaks were within this frequency range over a wide range of beam parameters. The time resolution of Figs. 5 and 7 are not

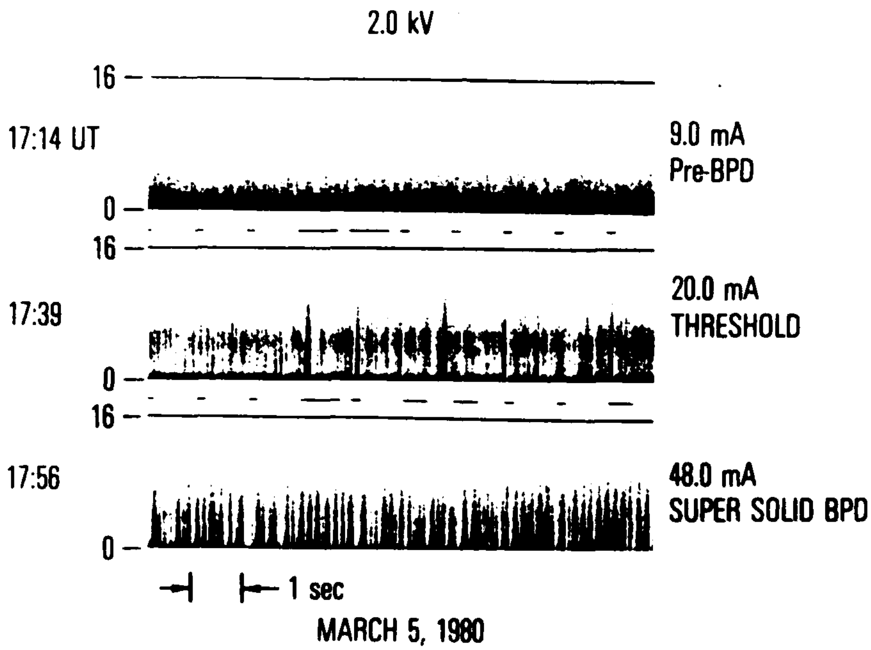

Fig. 5. Three 10-sec Samples of Spectrograms during Various Gun Currents at 2.0 kV

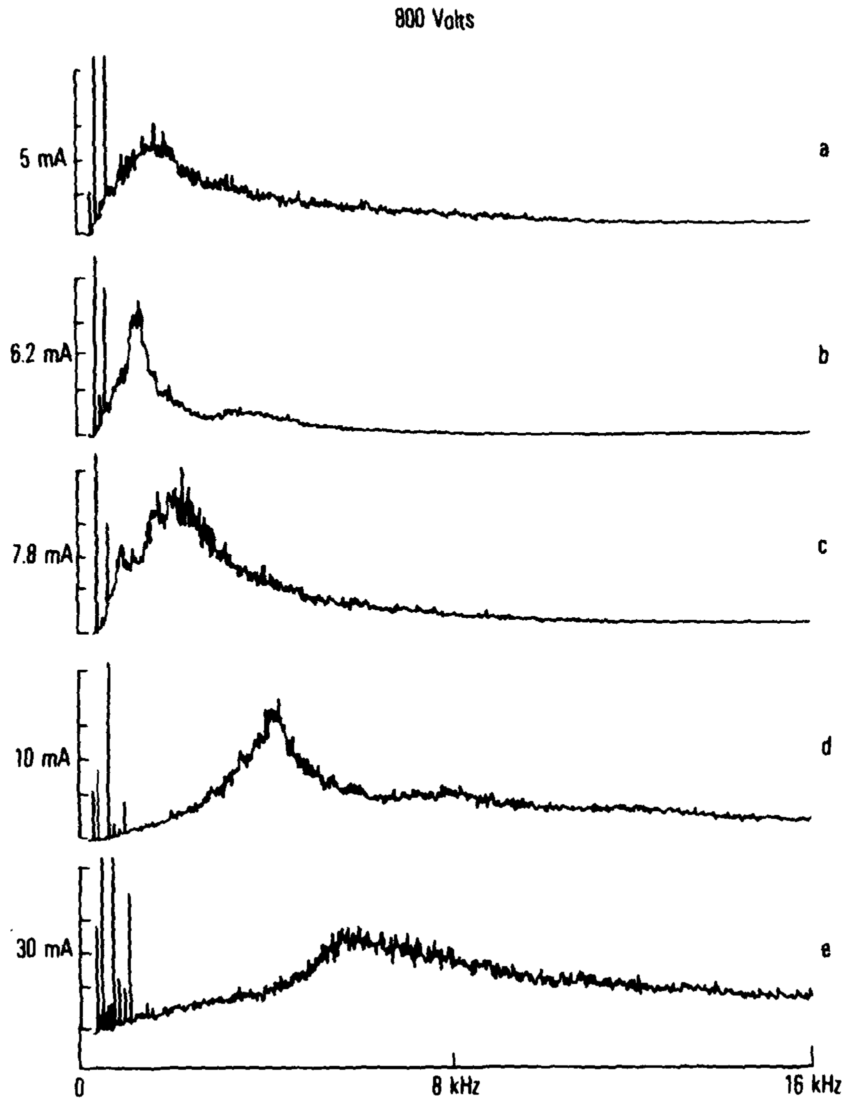

Fig. 6. Electric Spectra at 800 V for Beam Currents. 0 db for each panel is a. 37.8 mV; b. 150.0 mV; c. 150.0 mV; d. 37.8 mV, and e. 13.4 mV.

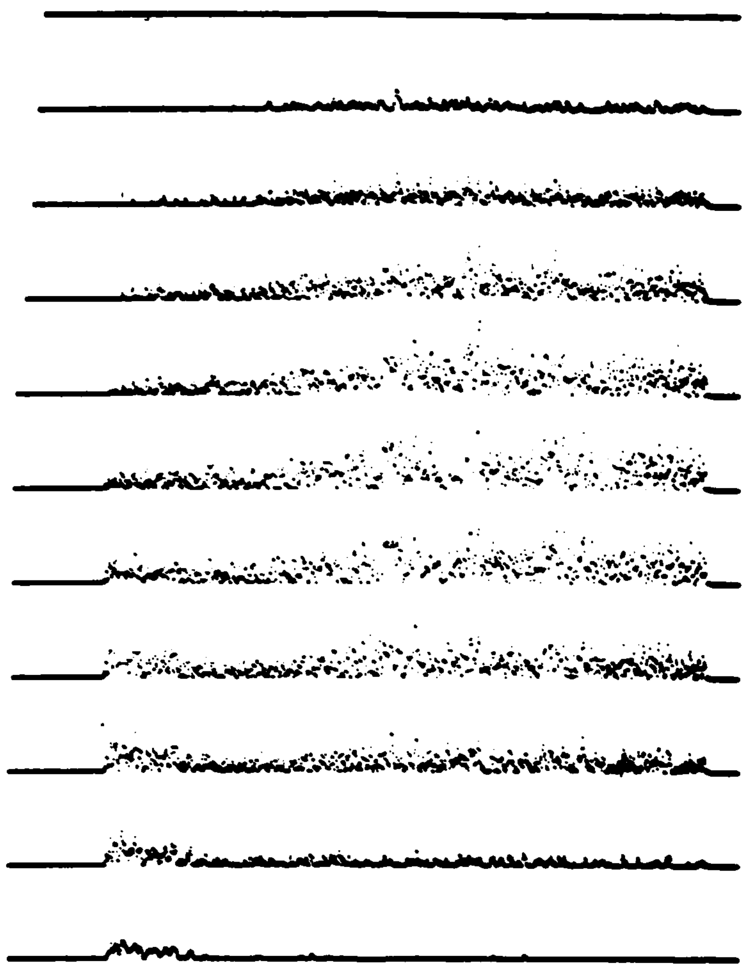

Fig. 7. Multiple Raw Spectra Taken during a Single 90-msec Gun Pulse Showing Single Particle Behavior at Start of Pulse (bottom) followed by Onset of BPD

high enough to show the exact beginning of BPD signature after gun turn on; however, Bernstein et al. (1981) have shown the BPD ignition appears within about a few milliseconds at these gun parameters. It cannot be stated absolutely, therefore, that the gun was pulsing in and out of BPD during the AMP's. However, it is believed that the ignition time is the time required to build a background plasma to the right density so subsequent maximum current pulses would build on previous conditions. Thus it is still expected that the 3-kHz AMP's at maximum gun voltage and current also produced BPD. Certainly the average spectra during AMP's (see Fig. 2) and during dc gun steps are similar. Unfortunately the ion gyroradius at 1 gauss is larger than the laboratory chamber for the data in Figs. 4 - 7 so ion gyrodynamics are not well modeled in the lab. However, the general spectral shape in Fig. 3 is very similar to that seen in Figs. 4c and 4d under similar conditions in the auroral ionosphere.

CONCLUSIONS

The VLF spectrum during beam plasma discharge can be characterized in general by the following:

1. The electric spectrum has a broad spectral peak typically between 1 and 16 KHz.
2. Peaks tend to move to higher frequencies or new peaks form as gun current increases.
3. The magnetic spectral signature can be considerably different from the electric, especially below the peak.
4. Electric field strengths of over 100 mV/m at the peak VLF frequency have been observed in the lab.
5. Effects near threshold can be highly spiky and turbulent with quasi-dc electric spikes over 10 volts/meter.
6. The spectral peak develops prior to BPD threshold conditions as determined by optical and rf measurements.
7. Background plasma densities are required for the BPD to occur as evidenced by a few milliseconds' delay in spectral change from gun turn on.

The rocket gun program operated at 0, 2 and 4 kV with maximum space charge limited currents of 0, 30 and 80 mA respectively. There is evidence for pulses in the rocket data at both the 2-kV step, and the 4-kV steps. Unfortunately, the chamber work was limited to 2 kV in these experiments. Also, the background electromagnetic noise above the lower hybrid was not modeled in the chamber. However, the general character of the VLF spectrum involving a rapid onset of a peaked spectral shape in the few kHz region, and the high time variability when taken with the photometric and particle energization data reported by Bernstein et al., 1979, strongly suggest that BPD occurred on this rocket flight.

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